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# IMPROVED COMPRESSION STRENGTH OF CARBON/GLASS/EPOXY HYBRID COMPOSITES

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## 1 Abstract

In the current study a number of new compression results are presented for filament wound, vacuum infused composites. Reinforcement fibers are typical glass and carbon products, commercially available and widely used in industry. Matrix resin is a slow curing epoxy designed for vacuum infusion of large components such as wind turbine blades. Compression testing was carried out on an in-house developed Mechanically Combined Loading fixture. Neat carbon/epoxy and glass/epoxy laminates were manufactured for baseline values. Hybrid composites of carbon and glass were manufactured in three different mix ratios. To further explore effects from hybridization an increased thickness specimen was prepared, along with a ply-ply specimen also of increased thickness. Specimens were analyzed for volumetric composition and found to have a very low void content.

Compression testing revealed a non-linear response from the neat carbon fiber composite, and subsequently also in the hybrids. In-ply hybrid specimens perform very close to Rule of Mixture (RoM), however with a failure strain governed by that of the neat carbon. An increase was however found with increasing glass content, though not enough to reach the same levels of compressive strength as the neat carbon or glass.

An increased failure strain was found for the ply-ply hybrid allowing it to reach strength values above the neat carbon fiber and glass fiber composites while still retaining the expected modulus as per RoM. A discussion is given concerning whether this result is due to a “hybrid-effect”.

## 2 Introduction

Due to recent trends concerning the ever increasing length of wind turbine blades, use of carbon fiber reinforcements in the main load carrying structure of the blade for higher stiffness has received increasing attention. The higher stiffness requirement is a result of maintaining tower clearance with respect to the tip deflection of longer blades. As a result of the high cost of carbon fiber, hybrid compositions of glass- and carbon fibers are interesting, as opposed to using prefabricated separate carbon/epoxy and glass/epoxy stiffeners. Difficulties of the latter include strength of adhesive joint, along with additional processing steps needed for fabrication, positioning and adhering stiffeners.

The term hybrid denotes composites with more than one type of reinforcement fiber [1]. Previously, this approach has been tested and disregarded, due to the low elongation at break of carbon fiber setting the upper limit for the strength of a hybrid, especially when loaded in compression [1]. That is, when the carbon fails, the stress level in the glass is only a fraction of the tensile strength of the glass [2]. This yields a material with lower failure strength than the respective constituents. From a wind turbine blade manufacturer’s perspective, letting the (compression) strength be the design driver would mean that the customer does not get full value of the expensive carbon used to increase the stiffness of the blade, which is not the ideal scenario. Since the compression strength of carbon has been measured to be as low as 50-80% of the tensile strength [3], this load scenario is particularly restrictive.

Hybrid materials of glass and carbon have, to a large extent, been shown to obey the Rule of Mixture (RoM) for elastic properties, however some scatter

have been seen in the determined strength properties [1,4]. For compression strength this is especially pronounced due to the large variation usually found in this type of testing. A direct comparison have also been difficult due to the extensive range of materials and manufacturing methods used [1,4].

Hybrids received a great deal of academic attention in the late 70ies and early 80ies [1,2,4,5,6] where the aim was to establish whether a “hybrid effect” could be found. The subject of much controversy the general consensus was however that the hybrid effect should entail an increase in the properties of the material greater than what was to be expected from RoM analysis. Focus was originally on using a High Elongation Component (HEC), usually glass fiber, to increase the elongation at break of a more brittle Low Elongation Component (LEC) usually carbon. Since no reports have been given in literature of a significant “hybrid effect” in the stiffness and strength of hybrid composites focus moved to the possibility of using alternating stacking sequences for improved bending stiffness and impact resistance [1]. This paper presents a number of new compression test results for carbon/glass/epoxy hybrid composite laminates. Different laminate hybrid architectures were investigated for a varying degree of hybridization. Results will be discussed with relation to their potential for validating the idea of a “hybrid effect” or whether deviations can be attributed to other phenomena.

## 3 Method and materials

### 3.1 Manufacturing

Due to the high cost and effort involved in having an experimental hybrid-fabric developed and manufactured, laminate specimens were filament wound. This was achieved using readily available constituent materials such as glass fiber roving and carbon fiber tows. Fibers used were commercially available fibers typically employed in Non-Crimp Fabrics (NCF's) for wind turbine blade manufacture. Matrix was likewise a typical commercially available industry grade slow-curing epoxy. Lay-up was achieved using an in-house house developed filament winding machine for rapid production of the test series (see Fig. 1).

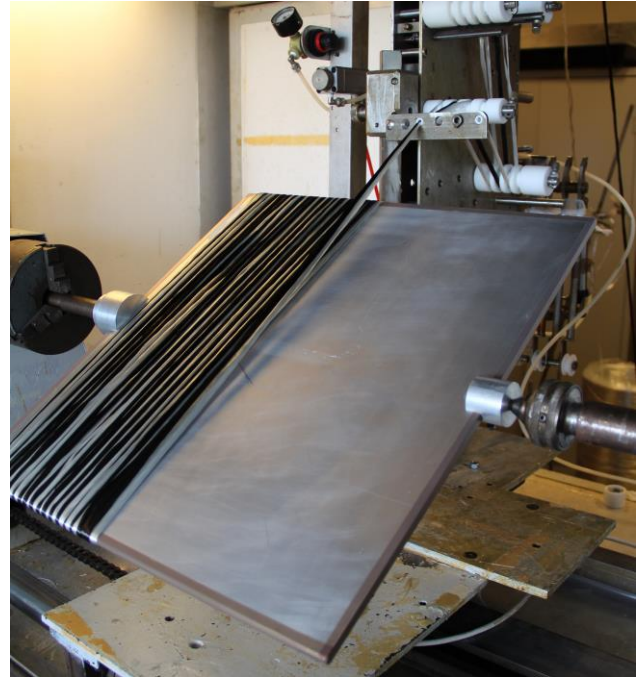


Fig. 1. Filament winding lay-up of carbon fibers and glass fibers on an aluminum tool plate.

Laminates with hybridization ranging from neat carbon/epoxy to neat glass/epoxy specimens were manufactured with three intermediate levels. Glass fiber roving and carbon tows were wound unto an aluminum tool plate pre-treated with a release agent. To achieve good and representative material quality manufacturing of laminates was realized using the Vacuum Infusion Process (VIP) (see Fig. 2). The laminates were cured for 5h@50C and post cured for 2h@90C. Overall this procedure enables good fiber-

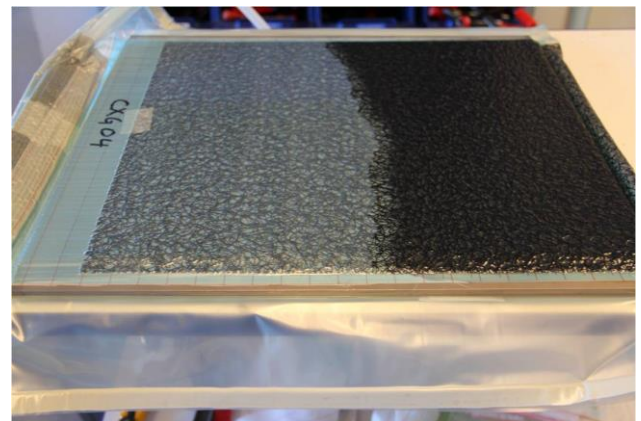


Fig. 2. Epoxy resin flow front moving over filament wound fibers in vacuum infusion process (VIP).

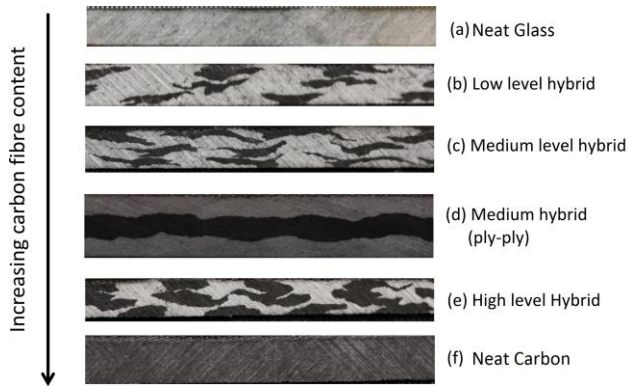


Fig. 3. Cross sections of manufactured laminates with different levels of hybridization and architecture.

alignment, absence of backing fibers and stitching yarn, low porosity levels, high fiber volume fraction and consistent material quality.

For the hybrid laminates the first three intermediates were realized with all rovings being applied simultaneously to the tool plate (as seen in Fig. 1). An important parameter to record is how homogenized the architecture is (size of unit cell), to ensure that the specimens cut are representative. The laminates are not completely without a pattern, and it was necessary to adjust the width to achieve a homogenous cross section for all specimens. The level of homogeneity has been established to be acceptable by measuring the content of the constituents in samples across the width of a panel, of the same width as a test specimen. Cross-sections of the realized laminates are seen in Fig. 3.

As an alternative to the in-ply architecture where both carbon and glass is present in a single ply, an attempt was also made at a ply-ply configuration, where the carbon and glass can be considered as

individual layers in a stack. This configuration is more homogenous across the width, and specimens can be cut at arbitrary width.

Neat carbon and glass laminates as well as the first three intermediate hybrids were made to a 3mm specified thickness. An additional medium level (in-ply) hybrid was made with a thickness of about 6mm, that is the maximum allowable thickness in the test fixture. This hybrid resembles medium level hybrid (c) in Fig. 3. This was done to investigate any size effect and to counter any potential problems with bending stability during testing. The addition of the ply-ply laminate to the test series was likewise chosen as 6mm to also counter these possible issues with bending stability. The reason why all specimens were not made as 6mm laminates is due to the inability of tensile testing carbon specimens of more than 3mm where the tab adhesive will usually fail in shear before specimen failure.

During manufacture special attention was given to investigate the actual wet-out of the fiber-assembly, due to the inclusion of both glass and carbon fibers. Flow direction was chosen to be along the length of the fibers, however due to the difference in fiber diameter and surface chemistry of the glass and carbon a number of issues could arise. The larger diameter of the glass fiber means that the resin will flow more easily and therefore faster, which entails the risk of incomplete wet-out of the carbon tows, especially at the center of the latter. Low porosity levels are not a clear indication of good wet-out because the volume involved in unwetted fibers is much less than that observed when encountering air entrapment and laminates manufactured with leaks. The ply-ply architecture posed a particular challenge because the dense carbon in the middle of the

Table 1. Result of volumetric analysis of tested composite laminates.

	Carbon $V_f$ [vol%]	Std. dev [%]	Glass $V_f$ [vol%]	Std. dev. [%]	Porosity $V_f$ [vol%]	Std. dev. [%]
Neat Glass	0,00	/	58,7	0,9	0,00	0,1
Low level hybrid	15,3	1,2	41,5	1,5	0,20	0,1
Med. Level hybrid	20,6	0,7	37,8	1,0	0,00	0,1
Med. Level hybrid (6mm)	21,0	1,0	38,1	1,1	0,17	0,1
Med. Level hybrid (ply-ply)	21,2	0,6	38,0	0,8	0,40	0,1
High level hybrid	30,8	1,3	27,6	1,4	0,20	0,1
Neat Carbon	53,0	0,3	0,00	/	0,07	0,2



“stack” acted as flow retardation, compared to the outer glass layers. Avoiding the flow in the outer layers reaching the outlet manifold and trapping air in the lower carbon and glass layers could only be achieved by using excessive brake length, thereby increasing the time of infusion significantly.

### 3.2 Analysis

To ensure adequate material quality, the fiber volume fraction (vol%) and porosity content was investigated using ASTM D2584 burn-off method and validated by SEM microscopy. Because the standard burn-off method would also consume the carbon fibers a controlled atmosphere burn-off method based on ASTM D2584 was developed for the neat carbon and hybrid laminates, in order to determine the fiber, matrix and porosity content. This method was validated by comparing the results for the neat carbon fiber laminate with the standard method of determining carbon fiber vol% using boiling sulphuric acid to dissolve the matrix. The standard deviation (std.dev.) for the vol% determination is presented in Table 1, as an indication of the consistency in material quality. The maximum average porosity volume fraction in all samples was below 0.4 %.

### 3.3 Compression testing

As a response to the large difficulty in obtaining consistent and reliable compression test data, a series of commercial and scientific projects have been carried out for a number of years at the Section of Composites and Materials Mechanics – DTU Wind Energy, in order to be able to support the wind energy industry with this challenge. For this purpose a Mechanically Combined Loading (MCL) compression fixture (schematic can be seen in Fig. 4) has been developed to overcome some of the limitations in other fixtures and methods [3,7]. One of the advantages of this fixture is its ability to maintain a fixed end to shear loading ratio, irrespective of specimen geometry and material strength, making it ideal for compression-compression fatigue testing.

Higher and more consistent strength results are some of the consequences of ensuring that optimum gripping (shear loading) and alignment of the test

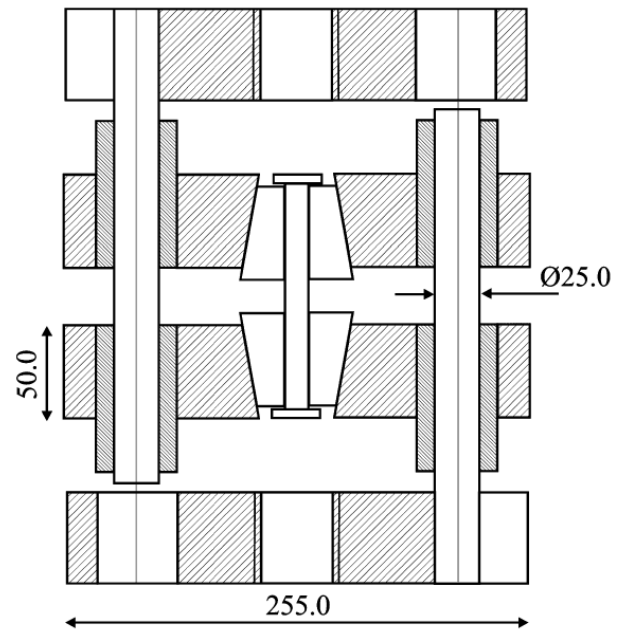


Fig. 4. Schematic of MCL compression fixture used for testing. [3]

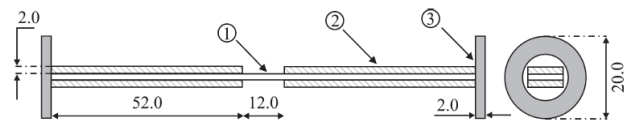


Fig. 5. Schematic drawing of compression test specimen with tabs and steel end-rings mounted [3]. Width and gauge length is different for tested specimens and drawing.

specimen is achieved throughout loading. Hence, the strength obtained is more reliable because bending of the specimen due to poor gripping and poor alignment is minimized. A full description of the test method and fixture design can be found in [3].

Testing was conducted using an Instron servo-hydraulic test machine (Instron, High Wycombe, UK) with a cross-head speed of 1mm/min. Strain gauges were mounted on both sides of the specimens to monitor alignment and parallelism, and record bending.

### 3.4 Test specimen preparation

All laminate plates had bi-directional glass fiber tab material mounted with a strong epoxy adhesive. Specimens were cut to final width on a water cooled diamond coated saw. A total of 10 specimens were tested in each series to ensure good statistical

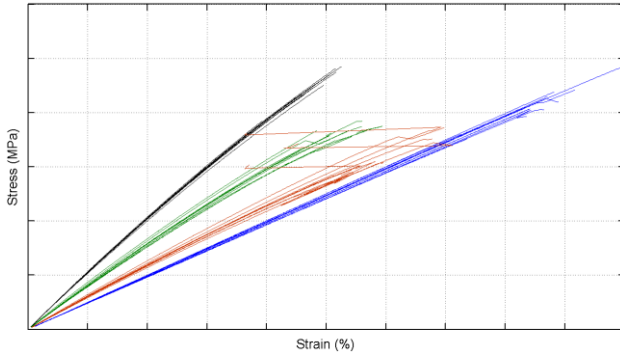


Fig. 6a. Measured compression test data for neat carbon, neat glass, high level hybrid and low level hybrid.

background. To avoid end splitting during loading, metal rings were mounted with glue on the ends of the specimens. Final test specimen dimension can be seen in Fig. 5.

#### 4 Compression test results

##### 4.1 Baseline- and 3mm in-ply hybrid composites

Neat glass/epoxy and carbon/epoxy composites were tested as baseline references in order to achieve elastic properties of the carbon and glass fibers. This can be used as constituent inputs for analytical linear Rule of Mixture (RoM) approximations for the hybrids. In Fig 6a compression test results for the baseline composites and medium in-ply hybrid composites of same thickness (3mm) is presented. In order to show the consistency in the test results the actual test read-outs from the averaged strain gauge measurement (for neat carbon, high level hybrid, low level hybrid and neat glass) can be seen in Fig. 6a. The medium level hybrid has been excluded from this figure to give a clearer representation of

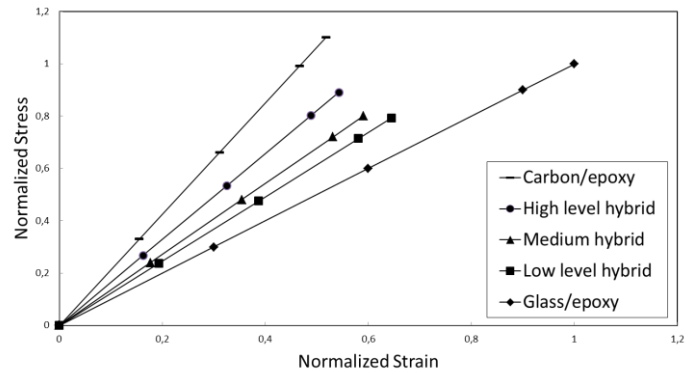


Fig. 6b. Compression test results normalized with respect to neat glass/epoxy specimen results. End points are failure strength and linear strain to failure.

the specimen grouping.

In Fig. 6b the data are presented in normalized form, with respect to the glass/epoxy specimen. An expected increase in stiffness and a notable decrease in failure strain are seen with increasing carbon volume fraction. The result of this is markedly lower compression failure strength. Hence, the low carbon fiber elongation at break is the limiting factor for the realized compression strength.

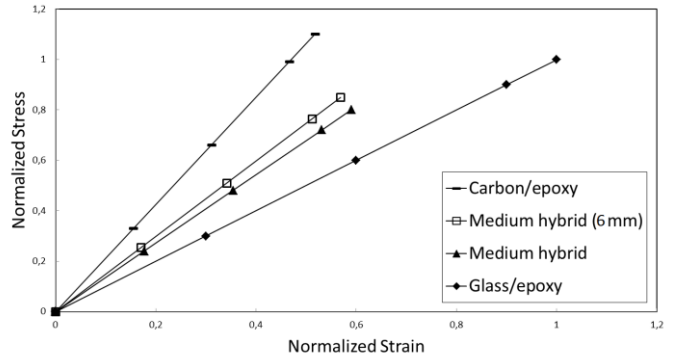


Fig. 6c. Comparison of results for 3mm and 6mm medium level hybrid laminates.

Table 2. Test results of strength, stiffness and failure strain normalized with respect to the glass/epoxy specimen results.

	E-modulus [/]	Std. dev [%].	Deviation from RoM	Max stress [/]	Std. dev [%].
Neat Glass	1.00	1.2	1.00	1.00	9.0
Low level hybrid	1.23	2.9	0.92	0.79	10.8
Medium hybrid	1.36	3.0	0.91	0.80	9.1
Medium hybrid (6mm)	1.49	1.9	0.99	0.85	6.0
Medium hybrid (ply-ply)	1.51	1.4	1.00	1.16	7.4
High level hybrid	1.64	3.0	0.95	0.89	2.8
Neat Carbon	2.13	1.1	1.00	1.10	6.5

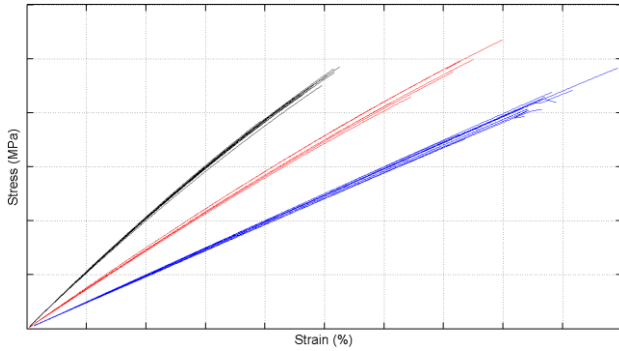


Fig. 6d. Measured data for carbon and glass benchmarks with 6mm ply-ply hybrid.

Commenting on the level of compression strength the values obtained for the neat glass and carbon fiber composites are quite close to those normally reported in literature for UD vacuum infused specimens, with similar failure strains. When using RoM the measured stiffness of the hybrid composites correspond very closely with back-calculated values from neat carbon and glass composites, as can be seen in Table 2. This reveals again that no “hybrid-effect” influences the elastic properties of the composite, which has also been shown many times in literature [1,2,4,5,6].

#### 4.2 Increased thickness specimens

Previous studies have shown that the test geometry of compression specimens can have a significant influence on the achieved results. In [8] the failure strain has been shown to decrease with increased gauge volume due to the larger statistical likelihood for presence of failure-initiating defects. In [9] the effect of specimen thickness was shown to influence the measured strength properties of composites tested in compression but not the modulus. Their method of testing was different however, with specimen thickness beginning at 6.4mm. The tested medium level in-ply hybrid with a thickness of 6mm was compared with the 3mm specimen of comparable hybrid fraction and found to produce a higher measured stiffness (see Fig. 6c). This is troublesome however not surprising, and puts focus on the importance of test specimen geometry. For comparative screening all specimens in a test series should retain similar dimensions and gauge volume.

As can be seen from Table 2 all elastic properties for

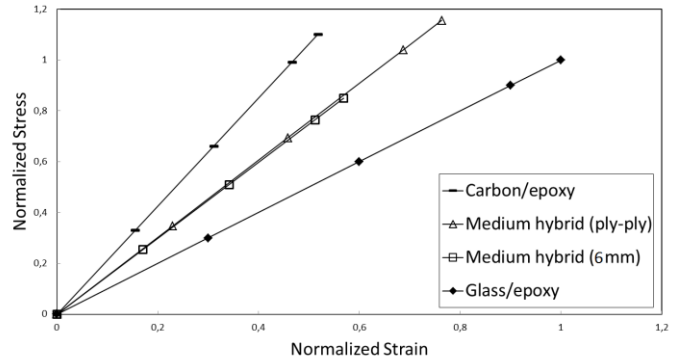


Fig. 6e. Normalized compression test results for carbon and glass benchmarks with 6mm in-ply hybrid compared to 6mm ply-ply hybrid

hybrid samples correspond very well with RoM analysis based on neat carbon and glass composites, however the thicker 6mm in-ply medium hybrid has a slightly higher modulus (norm. 0.99) compared to the other in-ply hybrids. This is, as stated, believed to be a size effect from test specimen geometry, and not a “hybrid-effect”.

#### 4.3 Ply-ply specimen

Even though the increased thickness in-ply medium hybrid does not have the same deviation from RoM prediction due to being of different test specimen geometry (and therefore cannot be directly compared to the rest of the series) it does however enable a comparison with the last type of specimen configuration. In an attempt to mimic a ply-on-ply laminate architecture, hybrid laminate specimen (d) (see Fig. 3) was manufactured with the same glass/carbon ratio as the medium hybrid (c) but with the carbon composite sandwiched between the glass composite layers. This combination proved most interesting in that it surpassed the ultimate strain of the corresponding 6mm in-ply hybrid with almost 30%, and achieved higher strength values than both the baseline glass/epoxy and carbon/epoxy specimens. See Fig. 6d for test data and Fig. 6e for normalized results.

#### 5 Discussion

Results for the volumetric composition of the tested specimens show good material quality with low void content and low standard deviations on the determinations carried out. Taking into account the extreme importance of unit cell considerations in the

hybrid context, the low standard deviation of the volumetric data both indicate that these are valid, but also that either the chosen specimen width is representative for the winding pattern or that the material is reasonably homogenous.

For the *mechanical test* results a quite low scatter was observed for elastic properties and a standard deviation around 5-10% for strength which is quite acceptable for unidirectional composites tested in compression. This can be observed in the figures as clear groupings.

*Failure modes* for glass composites were typical transverse catastrophic inside the gauge section. For all in-ply hybrids and neat carbon composites, the failure mode was almost exclusively longitudinal splitting along the fiber bundles. Whether the failure originates in the gauge section or in the tab region is difficult to discern since the failure affects both. As expected the failure looks to originate in the carbon tows and then spreading to the rest of the composite. The ply-ply hybrid has a different failure characteristic all-together. The outer glass layers look to have debonded from the sandwiched carbon layer and kinked outwards in the thickness direction. Inside the specimen the carbon layer seems to have failed in a typical micro-buckling kink-band.

The hybrid composites perform in good agreement with RoM for elastic property predictions. For in-ply specimens a modest improvement in failure strain (compared to failure strain of neat carbon) with increasing glass content was seen. This effect is however not enough to bring the failure strength to the same level as the neat glass or carbon specimens.

The upper limit of compressive strength seems to be insensitive to the fiber stiffness, supporting the work of Sørensen et.al [10]. There is a strong indication that the failure driver is to a greater extent governed by matrix properties.

Failure strength of in-ply hybrid composites seems to be limited by the neat carbon ultimate strain. This has been demonstrated previously for compression in [11]. Here the ply-ply architecture was also tested and proved to show increased failure strain, in tension. A possible explanation for the lack of increased failure strain in compression is probably

that their test series was based on woven fabrics. The detrimental influence of introducing misalignment by weaving the fibers has been well documented particularly in compression [12]. In all probability their test series are dominated by a completely different failure driver. In [13] pultruded carbon/glass hybrid composite rods were tested in compression and showed increased failure strain at compressive strengths similar to those in [11]. These were however significantly lower than in this study and using a different test method with pure end loading.

Looking at the cause of the extended failure strain of the ply-ply hybrid the most obvious explanation would be the influence of stress concentrations induced by the grips of the compression test fixture. This would also explain the results in [11] and [13]. It is widely acknowledged that in testing of a highly anisotropic composite like carbon/epoxy which is strong and stiff in the main direction but weak in shear, the obtained compression strength is conservative. This is because the test is not actually of the material in the gauge section but of the material exposed to the stress concentration. Studies have tried to determine the scale and importance of these stress concentrations [14,15]. Others have tried to measure the full compression strength in testing by adding off-axis layers to the composite and using the obtained failure strain to calculate the stress levels in the main layers [16].

Results from this series can be argued to give support to the theory that the highly anisotropic nature of the carbon composite makes it sensitive to the test method and makes it fail prematurely, as indicated in Bogetti et al. [7]. By doing this the initial assumption of Manders [2] is demonstrated also for compression, indicating that: “the hybrid effect arises from a failure to realize the full potential strength of the fibers in all-carbon composites, rather than from an enhancement of their strength in the hybrids”.

Whether or not this is then the upper limit for carbon composites in compression is also a topic of interest. When considering that failure of the ply-ply specimens occurred inside the gauge section it stands to reason that it is unaffected by stress concentrations near the grips. Applying more layers



to further reduce the gripping effect would probably not provide a noticeable improvement.

The results provided by this study could potentially pave the way for filling the gap in elastic modulus between glass fiber and carbon fiber with a range of hybrid compositions, without compromising on strength requirements. However since Pandya et al. [11] have already shown that this effect not necessarily can transfer to less “pure” composites, each individual fabric still has to be tested to see if the influence of weave/stitching/backing induces premature failure.

## 6 Conclusion

Hybrids of carbon and glass fibers have been used as basis for composite laminates of good quality. The filament winding manufacturing allows a controlled mix ratio of carbon and glass fibers to be used, and thus allows design of final composite stiffness and strength in the range from neat glass fiber composites to neat carbon fiber composites.

The compression properties have shown that hybrid composites have stiffness and failure strain between those for the neat fiber composites, while the values for strength is below those of both glass fiber composites and carbon fiber composites.

A special hybrid ply-ply configuration composite has shown intermediate stiffness and failure strain, but higher compression strength than both neat glass and neat carbon fiber composites.

This observation is discussed with respect to mechanisms and observations reported in the literature; no definite conclusion has been reached.

## Aknowledgements

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